

Effect of wall temperature on the growth of Gortler vortices in high-speed boundary layers

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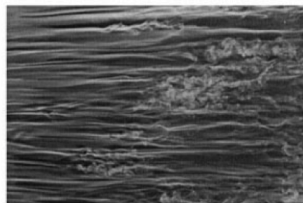
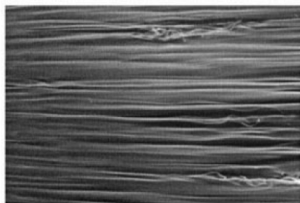
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APS Fluid Dynamics, November 2018

Boundary layer streaks

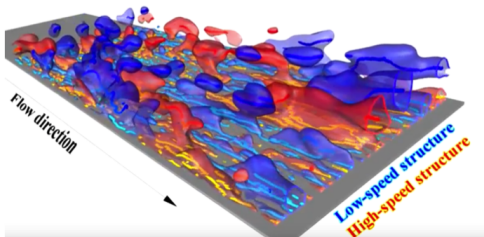
Klebanoff modes in bypass transition



Matsubara and Alfredsson, 2001, J. Fl. Mech.

Turbulent boundary layers

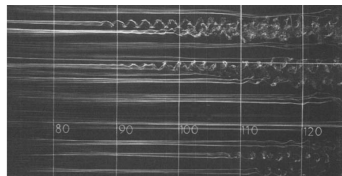
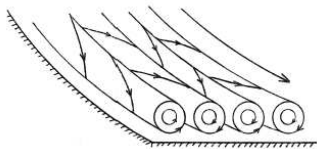
Lee, Sung & Zaki (J. Fluid Mech., 2017)



Lee, Sung & Zaki, 2017, J. Fl. Mech.

Gortler vortices?

-centrifugal instabilities in boundary layer flows over concave surfaces



Swearingen and Blackwelder, 1997, JFM

-previous studies and results indicated that the streaky structures in boundary layers are responsible for variations in the frictional drag or heat transfer

-so control methods must focus on restricting the development of these streaks.

We study the effect of wall cooling/heating to Gortler vortices in supersonic and hypersonic boundary layers

Scalings

We solve for the compressible Navier-Stokes equations (equations not included)

All dimensional spatial coordinates are normalized by the spanwise separation λ^* of the Görtler vortices, and the velocity is scaled by the freestream velocity magnitude V_∞^*

$$(x, y, z) = \frac{(x^*, y^*, z^*)}{\lambda^*}, \quad (u, v, w) = \frac{(u^*, v^*, w^*)}{V_\infty^*}, \quad (1)$$

and pressure is scaled by $\rho_\infty^* V_\infty^{*2}$, and temperature by the freestream temperature, T_∞^* . Reynolds number, Mach number and Prandtl number are defined as

$$R_\lambda = \frac{\rho_\infty^* V_\infty^* \lambda^*}{\mu_\infty^*}, \quad M_\infty = \frac{V_\infty^*}{a_\infty^*}, \quad Pr = \frac{\mu_\infty^* C_p}{k_\infty^*}, \quad (2)$$

The Görtler number based on the boundary layer momentum thickness, θ^* , is defined as

$$G_\theta = R_\theta \sqrt{\frac{\theta^*}{r^*}}, \quad (3)$$

Numerical method

- time integration: third order TVD Runge-Kutta method
 - spatial derivatives: dispersion-relation-preserving schemes
 - high-order filtering to remove high-wavenumber spurious waves
 - inflow conditions from a precursor 2D simulation
- shocks are not taken into account (no leading edge)

Grid:

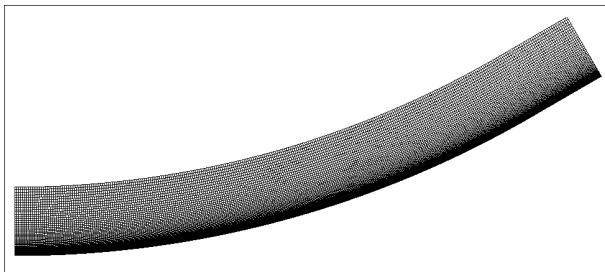
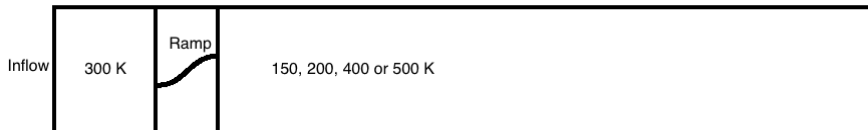


Table: Flow parameters.

Mach number, M	Unit Reynolds #	Görtler #, G_θ	Spanwise sep., Λ^* [m]
$M = 1.5$	1.40E+6	22.00	0.0120
$M = 3.0$	2.81E+6	23.31	0.0057
$M = 4.5$	4.18E+6	28.28	0.0043
$M = 6.0$	5.55E+6	31.45	0.0036
$M = 7.5$	7.09E+6	34.57	0.0031

The way we impose wall cooling or heating:



Grid convergence study

Table: Number of points in different grids.

Mach number	<i>grid1</i>	<i>grid2</i>	<i>grid3</i>	<i>grid4</i>	<i>grid5</i>
$M = 1.5$	329,232	990,000	1,771,200	2,763,600	3,830,400
$M = 3.0$	329,232	930,000	1,684,800	2,646,000	3,696,000
$M = 4.5$	329,232	870,000	1,598,400	2,528,400	3,561,600
$M = 6.0$	329,232	810,000	1,512,000	2,410,800	3,427,200
$M = 7.5$	329,232	750,000	1,425,600	2,293,200	3,292,800

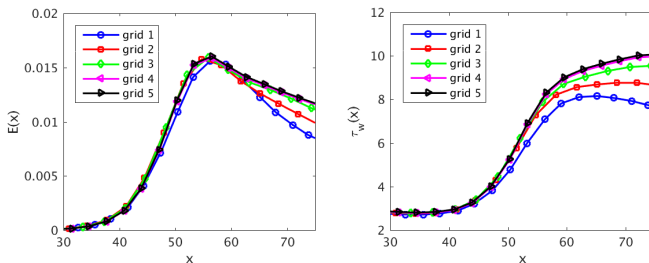
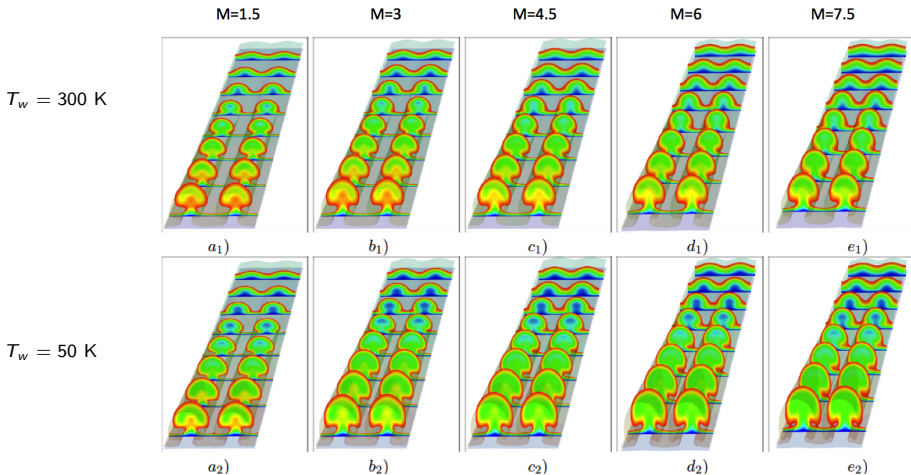


Figure: Vortex energy (left) and wall shear stress (right) for four grids of different resolutions.

Effect of wall heat transfer

Initially, we considered very low (unrealistic) wall temperatures: $T_w = 50$ K and $T_w = 100$ K



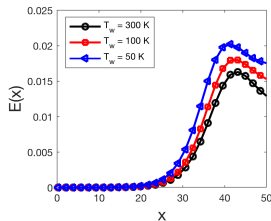
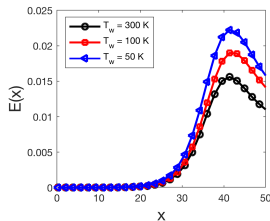
Results

Initially, we considered very low (unrealistic) wall temperatures: $T_w = 50$ K and $T_w = 100$ K

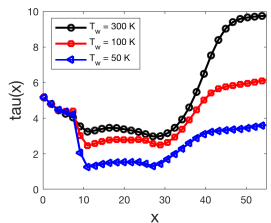
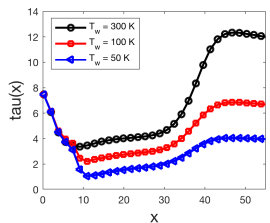
Energy

M=1.5

M=4.5



Wall shear stress

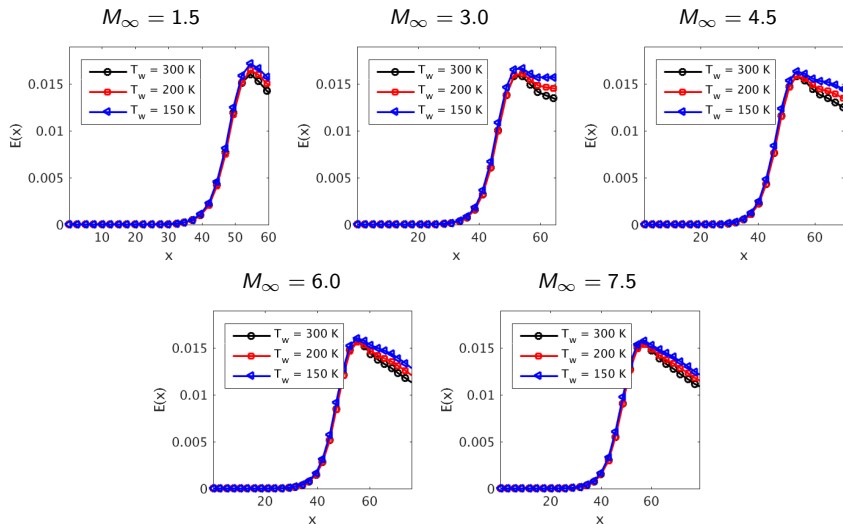


Results

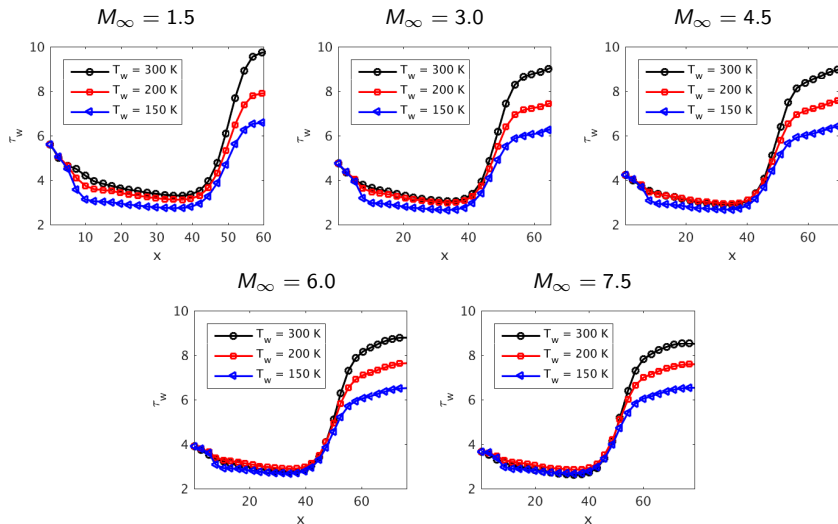
Then, more realistic cooling/heating: $T_w = 150, 200, 400, 500$ K.

Upstream: $T_w = 300$ K

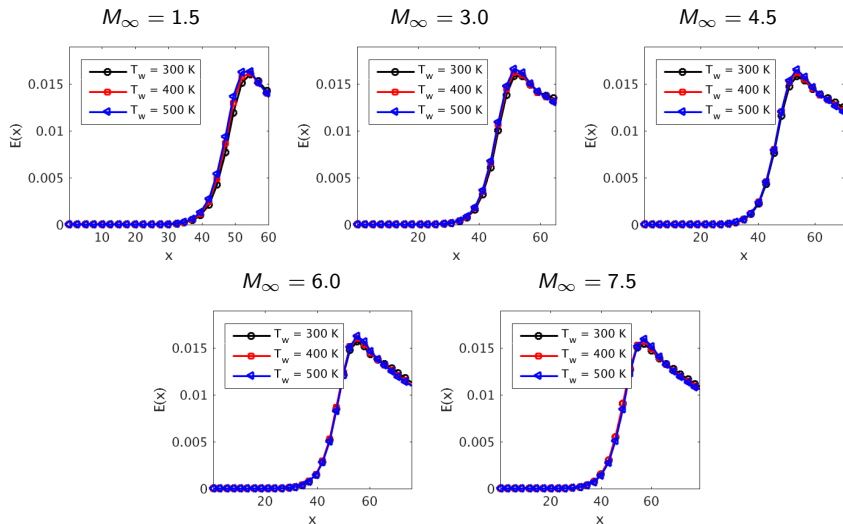
Vortex energy



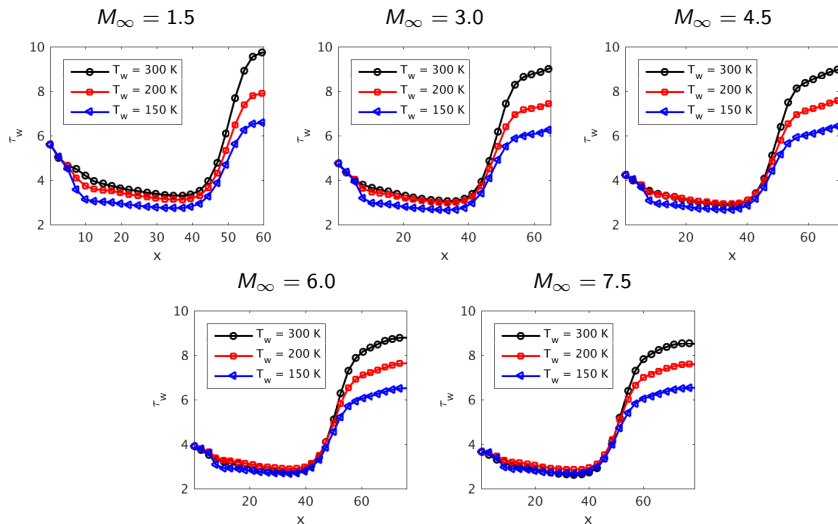
Realistic cooling - Wall shear stress



Heating - Vortex energy



Heating - Wall shear stress



Wall shear stress integrated over the entire wall surface

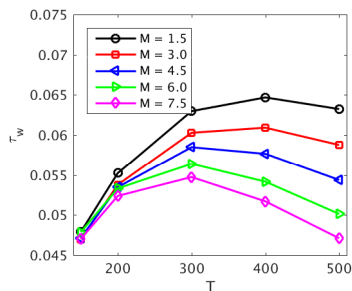


Figure: Skin friction drag as a function of the wall temperature and for different Mach numbers.

Conclusions:

A numerical study of the effect of controlled cooling and heating on the development of Görtler vortices in high-speed boundary layers has been performed.

The wall cooling or heating was imposed in the downstream of a wall temperature of $T = 300$ imposed in the proximity to the inflow boundary.

Results indicated that wall cooling/heating just slightly modify the streamwise evolution of the Görtler vortices.

Both wall cooling and heating decreased the spanwise averaged wall shear stress.

Future work will consider the application of cooling and heating to unsteady boundary layer streaks.

Thank you!